

Impact of cross-sectional uncertainties on DUNE sensitivity due to nuclear effects

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New Perspectives 2020

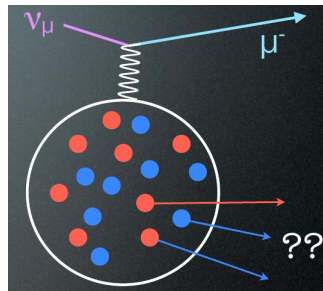
FERMILAB-SLIDES-20-099-LBNF

August 24-25, 2020



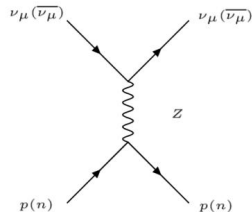
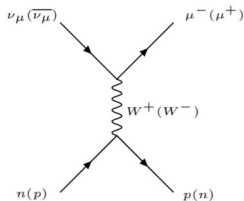
Outline

- 1 Neutrino-Nucleus Interactions
- 2 Nuclear Effects
- 3 Neutrino interaction models
- 4 Results
- 5 Summary

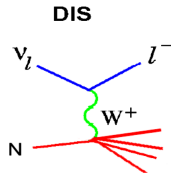
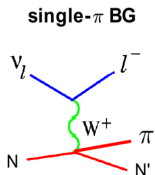
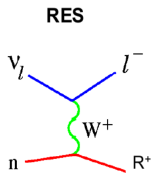
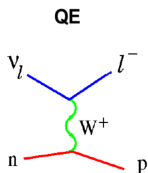


Neutrino Interaction Processes

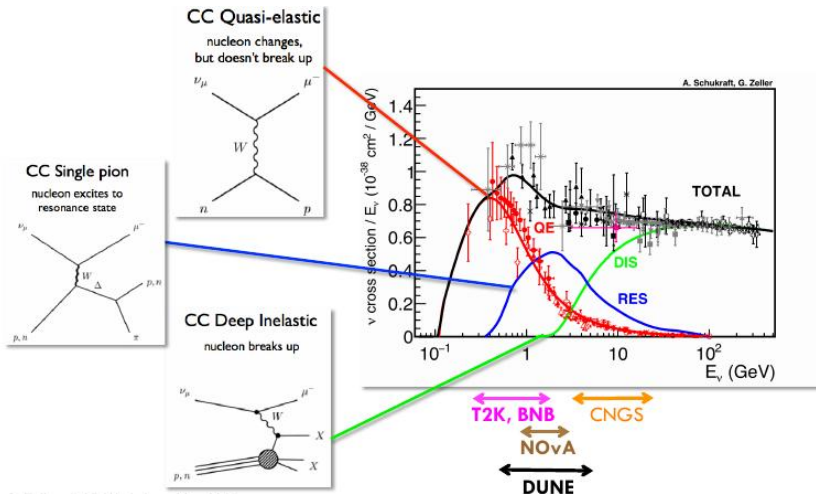
- A neutrino interacts via charged current or neutral current interactions.



- Various energy dependent neutrino interaction processes



Interaction Cross-section



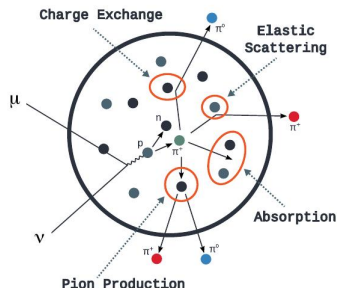
Nuclear Effects

• Initial State Interactions

- Nuclear Binding
- Fermi motion
- Pauli blocking

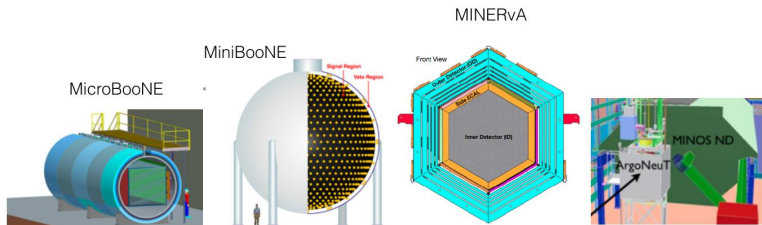
• Final State Interactions

- absorption of outgoing particles
- rescattering, charge exchange
- production of new particles



Nuclei as Targets: Why?

- To increase neutrino interaction rates: experiments use heavy nuclear targets with high atomic mass numbers like Ar($A=40$), C($A=6$), Ca($A=40$).
- Heavy nuclear targets gives a boost to the event statistics in turn reducing the statistical uncertainties but at the same gives rise to the systematic uncertainties which are ultimately required to be tuned.

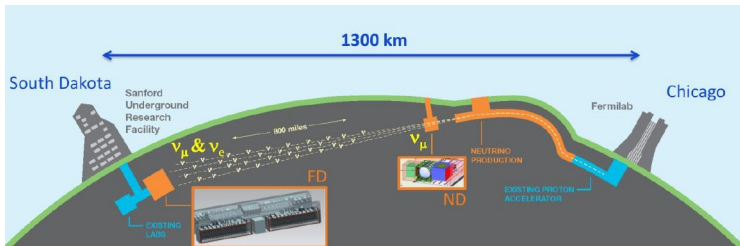


Uncertainties in the ν -nucleus cross-section

- Two main reasons:
 - poor knowledge of neutrino flux
 - recent cross section measurements have been performed on nuclear targets
- Neutrino experiments measure a convolution of energy dependent neutrino flux \otimes energy dependent cross-section \otimes energy dependent nuclear effects.
- Interacting neutrino energy is evaluated based on kinematics of particles in the final state, taking into account detector acceptance.

Deep Underground Neutrino Experiment

- A next generation experiment for neutrino science, nucleon decay, and supernova physics.
- It consists of a near detector (Fermilab) and a far detector (Sanford Underground Research Facility(SURF), South Dakota) placed at a distance of 575 m and 1300 km respectively from a megawatt facility situated at Fermilab, producing a muon neutrino beam.
- The FD will be composed of four, 10 kton each LArTPC.



Neutrino event generators: GENIE and GiBUU

- Both GENIE¹ and GiBUU² differ on the nuclear models and computation of different types of interactions.

GENIE

- ROOT based, object oriented methodologies
- vector form factor- BBBA05
- resonance modes- 16
- DIS- Bodek and Yang model
- FSI models- Intranuke hA and hN

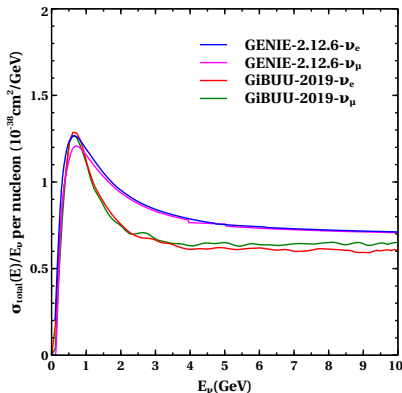
GiBUU

- based on a coupled set of semiclassical kinetic equations
- vector form factor- BBBA07
- resonance modes- 13
- DIS- PYTHIA
- FSI is modeled by solving the semi-classical BUU equations

¹C.Andreopoulos, Nucl.Instrum.Meth.A614 (2010) 87-104.

²O. Buss *et al*, Physics Reports, vol. 512, no. 1-2, pp. 1-124, 2012.

ν_e, ν_μ interaction cross-section: GENIE and GiBUU



We have considered the QE, RES from Δ resonant decay and contribution from higher resonances, 2p2h/MEC and DIS interaction processes. ³

³S. Nagu *et al*, Nuclphysb.2019.114888

Simulation Details

- A comparison of beamline parameters for Reference Design and Optimized Design flux are as follows. These parameters are used in our analysis ⁴.

Parameters	Reference	Optimized
Proton Beam Power	1.07 MW	1.07 MW
Energy of Proton Beam	80 GeV	80 GeV
Horn Style	NuMI-style	Genetic Optimization
Horn Current	230 kA	297 kA
Diameter of Decay Pipe	4 m	4 m
Length of Decay Pipe	204 m	241 m

⁴R. Acciarri, *et al*, DUNE Collaboration, arXiv :1512 .06148v2 [physics ins det], 2016.

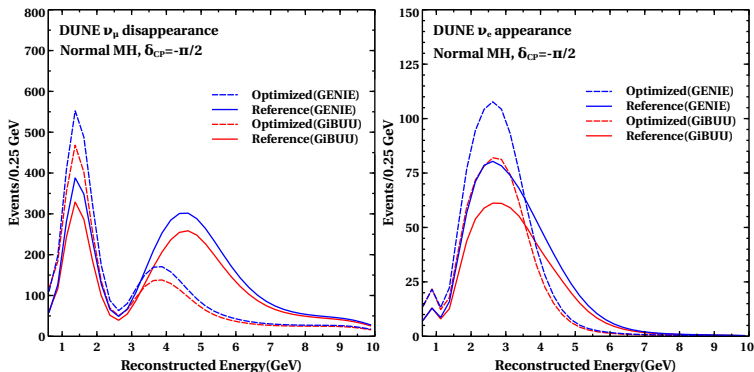
Oscillation parameters considered in our work ⁵

Parameter	Best Fit Value	3σ Range
θ_{12}	33.82°	-
θ_{13}	8.61°	-
$\theta_{23}(\text{NH})$	49.6°	$40.3^\circ - 52.4^\circ$
$\theta_{23}(\text{IH})$	49.8°	$40.6^\circ - 52.5^\circ$
δ_{CP}	0°	$-180^\circ - +180^\circ$
Δm_{21}^2	$7.39\text{e-}5\text{eV}^2$	-
$\Delta m_{31}^2(\text{NH})$	$2.525\text{e-}3\text{ eV}^2$	$+2.427 \rightarrow +2.625$
$\Delta m_{31}^2(\text{IH})$	$-2.512\text{e-}3\text{ eV}^2$	$-2.611 \rightarrow -2.412$

⁵Ivan Exteban *et al*, JHEP01(2019)106

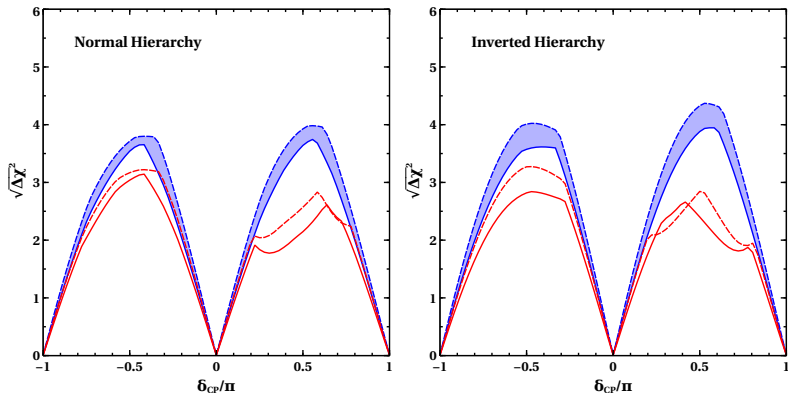
Event distributions

$$Event = \sigma \times \phi(E) \times N_T \times t$$



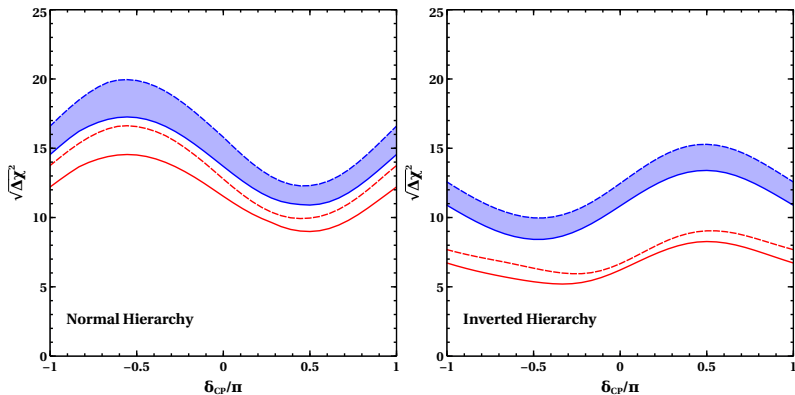
- ν_μ disappearance and ν_e appearance event distributions as a function of reconstructed neutrino energy for both reference and optimized beamline designs in the energy regime 1-10 GeV. (Generated using GLoBES)

Results- CP Sensitivity



$$\begin{aligned}\Delta\chi_0^2 &= \chi^2(\delta_{CP} = 0) - \chi_{true}^2 \\ \Delta\chi_\pi^2 &= \chi^2(\delta_{CP} = \pi) - \chi_{true}^2 \\ \Delta\chi^2 &= \min(\Delta\chi_0^2, \Delta\chi_\pi^2)\end{aligned}$$

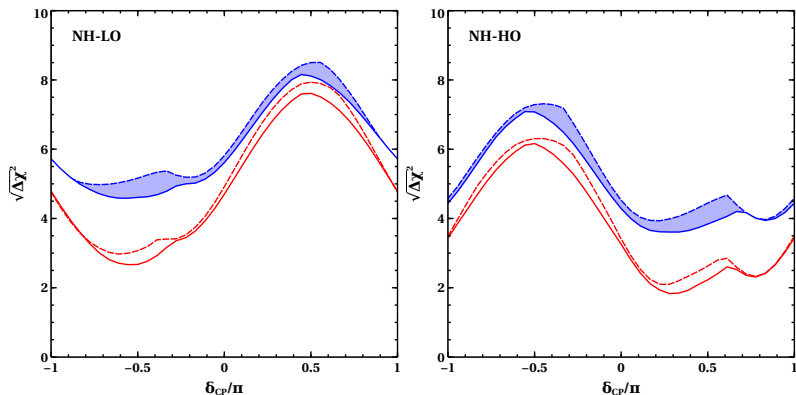
Results- Mass Hierarchy Sensitivity



$$\Delta\chi_{MH}^2 = \chi_{IH}^2 - \chi_{NH}^2$$

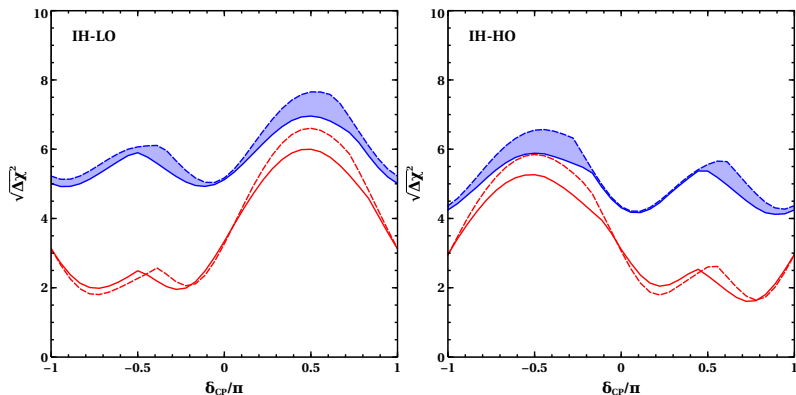
$$\Delta\chi_{MH}^2 = \chi_{NH}^2 - \chi_{IH}^2$$

Results- Octant Sensitivity (NH)



$$\Delta\chi_{octant}^2 = |\chi_{\theta_{23}^{test} > 45^\circ}^2 - \chi_{\theta_{23}^{true} < 45^\circ}^2|$$

Results- Octant Sensitivity (IH)



$$\Delta\chi_{octant}^2 = |\chi_{\theta_{23}^{test} > 45^\circ}^2 - \chi_{\theta_{23}^{true} < 45^\circ}^2|$$

Summary

- Construction of a nuclear model requires the precise combination of information about the energy dependence of all exclusive cross-sections and nuclear effects.
- The simulated results depend on this nuclear model where ignorance of theoretical uncertainties cost inaccuracy.
- Since nuclear effects are not well understood, thus different generators use different approximations to accommodate the nuclear effects giving rise to different results.
- Neutrino interactions with bound nucleons inside the nucleus needs proper implementation of nuclear physics in different simulation tools so that the results are independent of the selection of the neutrino event generators.

Thank you for your attention.

